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A Review of Very Large Vapor Cloud Explosions

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The UK Health and Safety Executive in collaboration with the Pipeline and Hazardous Materials Safety Administration (US Department of Transport) have carried out a detailed review of very large vapor cloud explosions (VCEs) associated with pipeline failures and losses of containment at refineries as well as LPG, LNG and gasoline storage sites. In the first instance this work is intended to inform assessment of the potential for escalation at LNG sites, in the case of an explosion following a significant leak of refrigerant gases (e.g. propane and iso-butane), but the findings are relevant to a wide range of petrochemical sites.

The review has focussed on two areas:

1. The relationship between weather conditions, source term and development of the flammable cloud.

Surprisingly, we have found that a majority of very large vapor cloud incidents occurred in *nil or very low wind conditions*. Rather than being catastrophic failures of large pipes or vessels, many of the most serious vapor cloud incidents were relatively small but sustained leaks, where vapor accumulated near the source and built up a substantial cloud over tens of minutes. In very low wind conditions, the clouds spread through the action of gravity with very low rates of entrainment; the flammable zone reached more than 500m from the source in several cases. The incident record suggests that small leaks in very low winds may be a more likely cause of major incidents than those catastrophic failures that produce a significant vapor cloud in any weather conditions.

2. Consequences of explosion in clouds with higher reactivity than methane

Examination of primary data from a number of LPG and gasoline incident investigations showed that in many cases severe overpressure effects extended to a high proportion of the cloud and the damage was not confined to areas where there was congested pipework or vegetation. In fact, we have not identified any reports of very large premixed clouds of gasoline vapor (with radius in excess of 200 m) which have burned slowly as flash fires. Notwithstanding the lack of pressure effects, such flash fires could cause deaths or injuries and would certainly have left a huge burned area. It seems likely that such occurrences would be reported in many parts of the world. The lack

of such reports suggests that if a very large gasoline cloud develops in a normal industrial context, the probability of a severe explosion is high. The situation for LPG is less clear cut: a significant proportion of large clouds caused by pipeline failures have burned as flash fires. The majority of these flash fires occurred in zero wind conditions and were probably very fuel rich.

The paper reviews the damage caused by test detonations on a range of common objects including overpressure-sensitive objects like drums and boxes and drag-sensitive columnar objects like scaffold poles and fence posts. The latter types of object exhibit a very characteristic distribution of plastic strain along the column length, resulting in continuous curvature rather than strain concentrated in plastic hinges.

Previously unpublished data from the Flixborough explosion are presented. The vapor cloud (extending up to 180 m from the plant) included many continuously curved poles and posts that matched the detonation test results. There is strong evidence that a large part of the cloud in this incident detonated.

The paper also presents data from the VCE at San Juan, Puerto Rico (2009). High quality photographic records and CCTV images allow the progress of this VCE to be reconstructed. The location in which transition to a severe explosion occurred is of particular interest in guiding risk assessment at other sites. The site of the San Juan explosion was also rich in lightweight columnar objects but no examples of continuous curvature were recorded. Other large VCEs at Buncefield (2005) and Jaipur (2009) showed similar characteristics on the basis of this evidence. It seems unlikely that these incidents were detonations. Video records of the speed of flame spread at San Juan support this conclusion.

The regular occurrence of severe explosions extending to the whole cloud has been recognised in the years since Buncefield. There has been a general presumption that this means that all such incidents were detonations, since this is the only mechanism for sustaining explosions in fairly open areas that has been demonstrated experimentally. There is now very strong evidence that there must be at least one other mechanism by which severe explosions in very large clouds can progress in open areas. The gap in scale between experiments and real clouds is very large; there was always a chance that important large-scale phenomena might have been missed. The paper examines one potential explanation for the observed behaviour that involves thermal radiation warming pre-mixed gas clouds ahead of the advancing flame front during a VCE. The analysis suggests that radiation effects may be the key to understanding the explosion mechanism in many incidents.

The paper concludes with a discussion of how the new data on vapor cloud explosions that has become available over the last ten years may affect risk assessment and emergency planning in the future.

Introduction

A total of 24 incidents were selected for review on the basis of the size of the area affected by the explosion, the scale of losses and the completeness of information available about the circumstances of the incident. The review collected data in the following areas:

1. Substances (gasoline, LPG, hydrocarbons used as refrigerants);
2. Source term (e.g. tank overfill, sprays, seal failure, hole size and release pressure);
3. Release size (duration of release, inventory);
4. Weather conditions (wind speed, stability);
5. Near field dispersion – especially the formation of a low entrainment, gravity-driven flow;
6. Cloud development (footprint, depth and influence of topography and surface roughness);
7. Explosion severity (flame speed and overpressure, distance of flame travel);
8. Blast damage to plant and other structures within and outside the cloud footprint;
9. Harm to on- and off-site personnel;
10. Information about the facility:
    a. Location (latitude/longitude), characteristics (ports, urban, rural, industrial, etc.);
    b. Maps of facility showing the property and surrounding area;
    c. Category of facility (possible categories - refineries, petrochemical, gas processing, terminals and distribution and upstream), description of facility;
    d. Number of similar facilities in the world;
11. Information about the incident and the engineering practices at the site:
    a. Description and cause of the release (e.g. operator error, equipment malfunction, material failure, construction or design error, weld failure)
    b. Mitigation measures in place and their effectiveness

An additional objective of the review was, where possible, to make publically available more detailed primary records of what happened in the incidents. These records include photographs of the aftermath and any video records of cloud accumulation and explosion. Four electronic multimedia packages have been prepared to allow wider access to primary data from the incidents at Buncefield (Buncefield Major Incident Investigation Board, 2007), Jaipur (MoPNG Committee, 2010), Flixborough (Flixborough Court of Enquiry, 1975) and San Juan (CSB 2015). The authors are indebted to the Chemical Safety Board (CSB) for making available a large amount of data from their investigation at San Juan.

Findings on vapor cloud formation

The incidents reviewed are listed in Table 1; this table also includes information about the rate at which hydrocarbon vapors were added to the cloud and the time between the start of the release and ignition. The data in Table 1 have been classified according to the wind conditions at the time of the release. This wind data comes from meteorological records and analysis of the cloud shape. For example, cases where the cloud spread in all direction around the source to a roughly equal extent are presumed to correspond to very low wind speed conditions.

Table 1: Summary of vapor transport conditions in the incidents reviewed

(mass release rates/durations included for non-pipeline failures – where known)

Incidents that occurred in nil/low–wind conditions		Vapor release rate (kg/s)	Duration prior to igniton (s)
Brenham, TX 1992	LPG Storage	100	3600
Newark, NJ 1983	Gasoline storage	35	>900
Big Spring, TX 2008	Refinery	not known	500
San Juan, Puerto Rico 2009	Gasoline storage	50	1560
Skikda, Algeria 2004	LNG facility	~10	<300s
Buncefield, UK 2005	Gasoline storage	19	1380
Amuay, Venezuela 2012	Refinery LPG storage	67	4080
Jaipur, India 2009	Gasoline storage	34	4500
Austin , TX 1973	LPG pipeline		
North Blenheim, NY 1990	LPG pipeline		
Donnellson, IA 1978	LPG pipeline		
Ruff Creek, PA 1977	LPG pipeline		
Incidents that probably occurred in nil/low-wind conditions			
Port Hudson, MO 1970	LPG pipeline		
St Herblain, France 1991	Gasoline storage	not known	1200
Geismer, LA 2013	Petrochemicals	not known	
Naples, Italy 1995	Gasoline storage	20	5400
La Mede, France 1992	Refinery	25	600
Incidents that occurred in light or moderate winds			
Baton Rouge, LA 1989	Refinery	681	150
Norco, LA 1988	Refinery	257	30
Pasadena, CA 1989	HDPE	643	60
Flixborough, UK 1974	Petrochemicals	670	45

Devers, TX 1975	LPG Pipeline		
Lively, TX 1996	LPG Pipeline		
Ufa, USSR 1989	LPG Pipeline		

It is notable that the incidents studied fell into two distinct groups:

1. Large releases (>250 kg/s) in light or moderate winds. These catastrophic releases were ignited rapidly as vapor was convected downstream – typically within 100s.

2. Smaller releases (<100 kg/s) in very low or nil wind conditions. These smaller releases accumulated over longer periods – typically several hundred or thousands of seconds. Vapor typically flowed away from the source in all directions – driven by gravity (Fig 1).

Figure 1: CCTV image of the vapor cloud at Buncefield - well away for the source. The flat upper surface indicates a laminarised flow.

The large proportion of incidents (71%) that corresponded to relatively small leak rates and accumulation of vapor in very low winds was initially surprising. In fact, these results suggest that incident scenarios involving dispersion in nil or very low speed wind conditions may dominate the total explosion risk at many sites.

This finding has been investigated further by modelling the dispersion of a flashing release of 49 tonnes of liquid propane from a 30,000 gall tank (80% fill) through a 2” hole (32 kg/s). The tank emptied in 1526 seconds. The area covered by the flammable cloud in D2 conditions - which corresponds to a 2 m/s wind speed and stability class D (Pasquill, 1961) - was studied with PHAST (DNV, 2013). If the jet was directed or deflected upwards the size of the flammable cloud was zero or very small (<< 1 acre). The worst case of a jet aligned with the wind (which is rather unlikely) gave an area within the LFL contour of ~ 2 acres. Note: 1 acre = 4,047 m² = 0.4047 hectares = 0.004047 km²)

On the other hand, analysis of the size of the cloud in very low wind conditions by the method described in FABIG Technical Note 12 (Atkinson and Pursell, 2013) gave a maximum flammable cloud size of approximately 150 acres.

In practice, many of the vapor clouds studied in the review covered areas of order 100 acres before ignition and we conclude that the density of ignition sources in these cases was of order 0.01 per acre. It follows that even in the worst case, the ignition probability for the 2" propane release in F2 conditions is 2% or less; whereas the ignition probability if the cloud is allowed to accumulate in still conditions may be close to 100%.

This illustrates why nil or very low speed conditions appear to dominate the records of major incidents: these weather conditions are somewhat rarer than light winds but they are associated with very large clouds and the risk of ignition is very much higher. Also very low wind conditions allow the development of a cloud that has the potential to cause a major accident for relatively low rates of vapor release. Such losses of containment are much more likely than large release rates (at least for non-pipeline incidents).

What wind speeds qualify as "nil or very low"?

Normally nil/low-wind conditions develop in stably stratified atmospheric conditions and are easily recognised. The density gradient near the ground is sufficient to suppress turbulent mixing in the lowest part of the atmosphere; this occurs when the Richardson number (*Ri*) is greater than about 0.25 (Grachev et al, 2013):

$$Ri = \frac{g\Delta\rho h}{\rho_0 u^2} > 0.25 \quad \text{where}$$

$\Delta\rho$ is the (total) density difference across the stably stratified boundary layer,

ρ_0 is the ambient density,

h is the depth of the stable layer,

u is the speed of the overlying airflow,

g is the gravitational acceleration (assumed to be 10 m/s^2).

Typical values in a stable boundary layer are $\Delta\rho / \rho_0 = 0.01$ and $h = 30$m (100 ft). The condition $Ri > 0.25$ implies $u < 3.4$ m/s. So, as a rule of thumb, if the overlying wind speed is 3 m/s or less the wind at ground level will drop out completely in conditions of rapid ground cooling (e.g. in clear conditions when the sun goes down). When the stable gradient decays (normally a little while after sun rise) the overlying wind can penetrate to ground level and nil/low-wind conditions cease.

It is possible for very low wind speeds in stable or neutral conditions to give laminarised vapor flows that are dominated by gravitational slumping and which entrain air very slowly. Work by Briggs et al (1990) on detrainment of heavy gas from depressions is useful in analysing this problem. Briggs showed that detrainment (stripping) of heavy gas from a pool in a depression occurs close to the upstream edge of the pool. As the current of air reaches the edge of the pool the boundary layer thickness (and hence the Richardson number) is necessarily small and turbulent mixing – entrainment of the heavy gas – must occur. As the mixing layer thickens the Richardson number increases until at some point it is large enough for further entrainment to be suppressed. Normally this thickening occurs fairly close to the upstream edge and there is no entrainment over the rest of the pool.

Briggs found that the rate of (volume) detrainment of the heavy gas per unit width of pool exposed to the crosswind was:

$$V = 0.05\frac{U^3}{g'} \qquad \text{where}$$

U is the flow speed over the surface and g' is the reduced density:

$g' = g.\ \Delta\rho/\rho$

Note this detrainment rate is not a function of the downwind length of the pool of heavy gas – because detrainment only occurs close to the upstream edge.

The flow is illustrated in Figure 2: this shows how gravity driven flow can occur beneath a light wind. The rate of entrainment of air into the bulk of the heavy current is very low and the vapor cloud can travel many hundreds of metres with only small reductions in concentration. This means that if the cloud is in the flammable range when it laminarises close to the source, then it will remain flammable even in areas near the cloud edge.

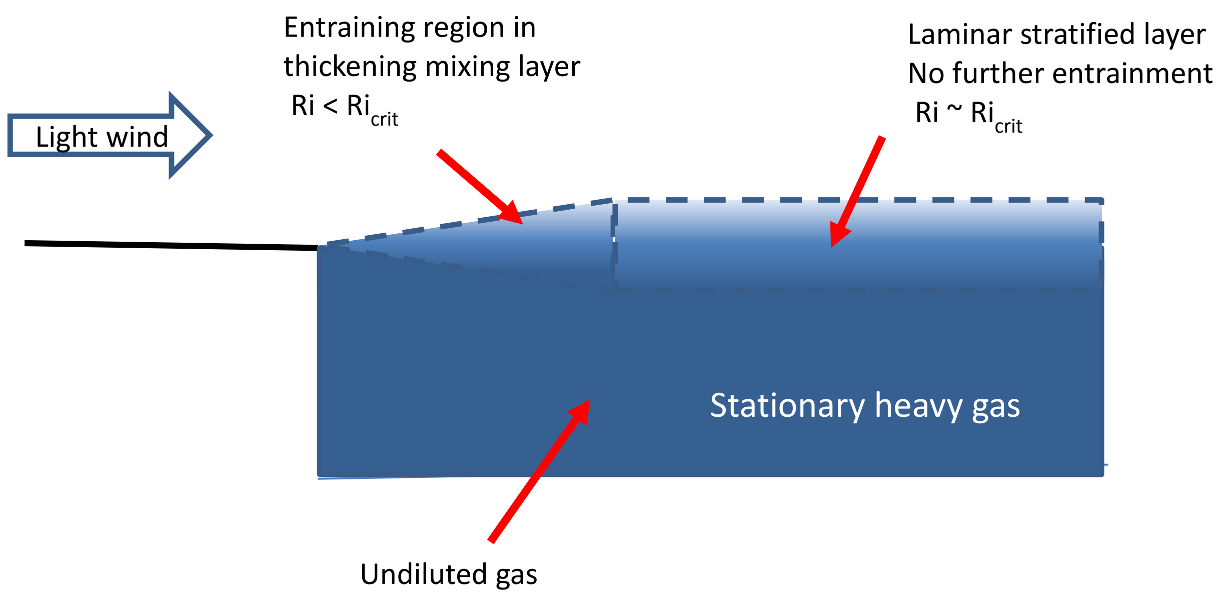


Figure 2: Detrainment of a heavy gas by a light wind

Brigg's detrainment formula can be used to estimate the critical Richardson number at which entrainment stops. If it is assumed that the gas volume fraction and velocity vary linearly across the mixing layer which is of depth h then integration of the product of volume fraction and flow speed across the layer gives the volume flux D of detrained gas (per unit width) as D = Uh/6.

The depth h will stop increasing when $Ri = g'h/U^2 = Ri_{crit}$

Substituting for h from the equation above gives $Ri_{crit} = g'\ 6D\ /\ U^3$

Comparing with the Brigg's formula gives $Ri_{crit} = 0.05\ x\ 6 = 0.3$

A typical range value for the density difference in a vapor cloud is Δρ/ρ =0.05 to 0.1 which leads to g' = 0.5 to 1. A typical value for the depth of the whole heavy layer is h = 2 m. The condition for laminar (non-entraining) flow in a stratified layer in the top 25% of the gas flow (with undiluted heavy gas flow beneath) is h = 0.5m

Substituting into the formula $Ri_{crit} = g'h/U^2 = 0.3$ gives an upper limit of wind speed of

$U < 0.9$ m/s for $g' = 0.5$ m/s^2

$U < 1.3$ m/s for $g' = 1$ m/s^2

Low wind speeds (< 1.3 m/s) are consequently required to allow gravity driven vapor transport with minimal dilution. For wind speeds greater than about 2.5 m/s, the mixing layer will not be able to deepen sufficiently to prevent entrainment over the bulk of the pool and the heavy gas will rapidly disperse.

Note these limits on wind speed apply at the top surface of the heavy gas flow – i.e. at a height of about 2 m. Wind speed data is normally recorded at a height of 10 m and there can be a significant drop in speed closer to the ground, depending on the roughness length. For roughness length 0.1m (which is typical of general agricultural land with a few scattered obstacles) the ratio of wind speeds at a height of 10 m and 2 m is $U(10m)/U(2m)$ ~1.5.

The condition for 75% of the gas cloud to remain undiluted (based on wind speeds measured at 10m) becomes:
$U(10m) < 0.9 \times 1.5 = 1.35$ m/s   for $g' = 0.5$ m/s^2

$U(10m) < 1.3 \times 1.5 = 1.95$ m/s   for $g' = 1$ m/s^2

The Briggs formula provides a means of estimating the potential maximum size of vapor clouds if the loss of containment is not stopped. It is assumed: that the cloud is circular; that near-source dilution is to a stoichiometric concentration of 0.076 kg/m^3 and that the value of reduced gravity is $g' = 0.5$ m/s^2. The cross-wind extent of the vapor cloud may increase until the rate of detrainment matches the rate of volume addition by the source. Equilibrium vapor cloud diameters are shown below for various hydrocarbon release rates and wind speeds.

Table 2: Equilibrium cloud diameters (m) at various values of mass release rate and wind speed

Mass release rate (kg/s)	Wind speed (m/s) 1 m/s	2 m/s	3 m/s
10	1316 m	164 m	49 m
25	3289 m	411 m	122 m
50	6579 m	822 m	244 m

For the lowest value of wind speed (1 m/s) the maximum potential cloud size is very large and in practice the maximum size of an unignited cloud is likely to be limited by the time for isolation of the leak or complete loss of inventory.

The idea of a secondary source or gas blanket covering the leak is a feature of some heavy gas dispersion models designed for windy conditions e.g. DEGADIS (Havens and Spicer 1988). The gas blanket grows until it is large enough for the rate of detrainment to match the gas input rate. Our review of incidents suggests that a high proportion occur in low wind conditions where the rate of detrainment is small compared with the feed rate. The gas blanket grows throughout the release as only a small proportion of the release gas is actually carried away. The volume of the cloud is set by release conditions and entrainment rates prior to laminarisation but the cloud shape is a function of topography around the site. Increases in ground elevation of 2-3 m are sufficient to stop the progress of the gravity driven flow. On flat sites the cloud is observed to spread roughly equally in all directions but, in several of the cases reviewed, vapor flowed along valleys and accumulated in hollows.

Forensic analysis of blast damage

Forensic techniques for the interpretation of blast effects have improved greatly in the last ten years, especially for low lying vapor clouds. Pressure-impulse diagrams are now available for some standard objects like drums and steel boxes that are sensitive to overpressure (crushing) damage (Chen, 2013). It is possible to identify severe explosions (defined here as those generating overpressures in excess of 2000 mbar or 29 psi) with confidence by examining such objects. Detonation tests have also demonstrated the type of damage to be expected in that type of explosion (SCI, 2014).

In low-lying clouds over relatively flat open areas, the direction of breakage of trees and posts gives a useful indication of the direction of explosion propagation (SCI, 2009). This type of analysis has been used in some of the cases reviewed to identify the location of the point of transition where a flash fire accelerated to become a severe explosion.

There is also a previously undocumented means of discriminating between different types of severe explosion based on examination of slender, columnar objects such as lamp posts, scaffold tubes, fence posts etc. In detonation tests and some vapor cloud explosions, these objects display a characteristic pattern of distributed plastic deformation which leads to continuous curvature along the length rather than concentration of plastic deformation in “hinges”. This behaviour is associated with the very high impulsive loads experienced during the normal impingement of a detonation. These loads accelerate lightweight spars on a time scale that is short compared with the transit of (elastic) flexural waves from points of restraint. Continuously curvature is very easy to spot in incident photographs and if it can be established that a spar has not been affected by a prolonged fire, then the curvature is a very good indicator that detonation has occurred. Fast deflagrations do not produce the highly impulsive forces required.

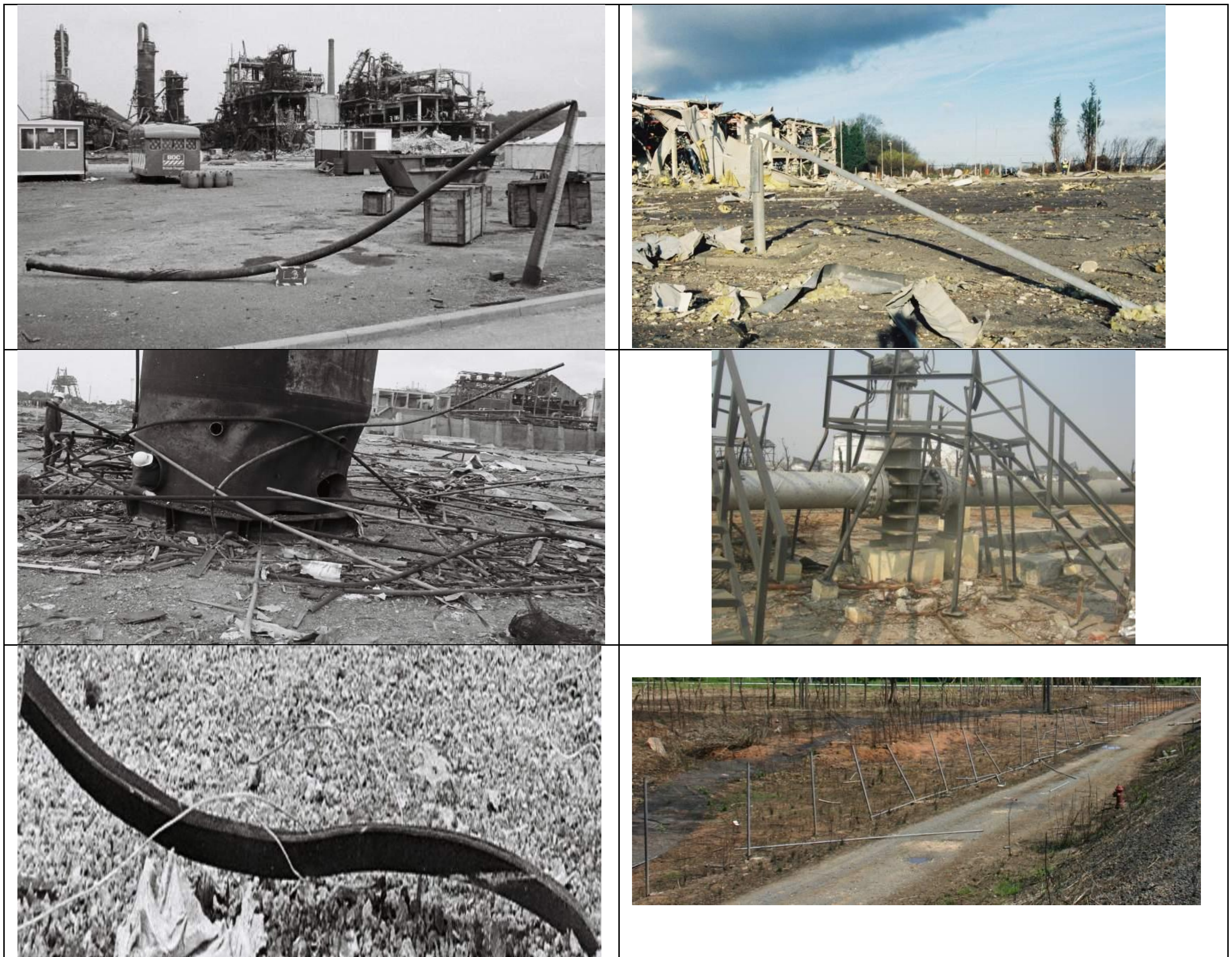
Review of blast damage in incidents

In many of the incidents reviewed there was clear forensic evidence that a severe explosion had propagated into open uncongested areas (Atkinson, 2015). This was a feature of all of the large vapor cloud incidents for which detailed primary evidence was available and is very likely to have been the case in all of the incidents. This observation challenges the normal assumptions made in blast damage assessment using, for example, the Multi-Energy Method (Van den Berg 1985) in which it is normally assumed that high overpressures are only sustained in congested areas.

In the years since Buncefield it has been recognised that severe explosions frequently extend to the whole cloud. There has been a general presumption that this means that all such incidents were detonations since this is the only established theory that allows sufficiently rapid burning to be sustained in open areas. The results of this review cast doubt on this presumption: there are serious discrepancies between the effects of experimental detonation on a variety of objects and what has been observed at most severe VCE incidents. For example, as noted above, normal impact by an experimental detonation can leave slender column-like objects with continuous curvature and this has also been observed in a wide range of objects at Flixborough. However no objects with this type of deformation have been observed at the sites that have previously been presumed to have been detonations: Buncefield, Jaipur, Amuay and San Juan (Figure 3). Similar discrepancies have been noted for all of the other types of damage e.g. the deformation of drums, boxes and vehicles: the impact of a detonation is associated with very high impulsive forces on the upstream face and corresponding asymmetric deformation (Figure 4). This type of damage was not observed in the fast deflagration incidents at Buncefield, Jaipur, Amuay and San Juan.
It is consequently appropriate to critically examine the assumption that has underpinned VCE assessment for the last 30 years namely that (unless Deflagration – Detonation Transition , DDT occurs) high overpressures are confined to congested areas. The incident data suggest that severe explosions can progress by a different mechanism: one that has not yet been observed in experimental tests on congestion arrays in gas tents. There is a large gap between the scale of clouds in real incidents and available test data and it was always possible that very-large scale phenomena might have been missed.

The data suggest that this new type of explosion is episodic in nature (Atkinson, 2011a, 2011b, 2015). Rapid phases of burning are punctuated by pauses. The overall rate of progress of the flame is sub-sonic. This effect is shown directly in CCTV footage of the explosion at San Juan.

It is suggested below that, at very large scale, radiation may play a key role in driving explosions. Pressure waves from a severe, localised explosion may disturb particles on the ground and other surfaces. Thermal radiation impacting on such re-suspended particles would lead to pre-warming of the surrounding gas and the development of an area ahead of the flame where the gas is warmer and consequently more reactive. At some point this warmed gas could react violently, producing a localised explosion capable of re-elevating more particles and sustaining the episodic combustion.



Above (left)

Detonation damage at Flixborough

Above (right)

Deflagration damage at Buncefield , Jaipur, San Juan

Below (left)

Detonation test

Figure 3: Damage to slender columnar objects: lamp posts, fence posts, scaffold poles etc.

Figure 4 : Damage to near full drums:

a. Incident (Jaipur) – symmetrical deformation
b. Pressure test (2 bar) – symmetrical deformation
c. Detonation test (arrow indicates deformation on the side impacted by detonation)

Evidence from the review on transition to a severe explosion

The transition to a severe (but not detonative) explosion regime seems to involve some degree of congestion or confinement. Based on the incidents studied, the following may act as triggers: confined explosions in buildings (e.g. pump houses), dense vegetation, pipe racks and other moderately congested plant. Figure 5 shows the area in which the transition to a severe explosion was observed to occur in the San Juan incident. The extent and density of congestion required is substantially less than that required for DDT.

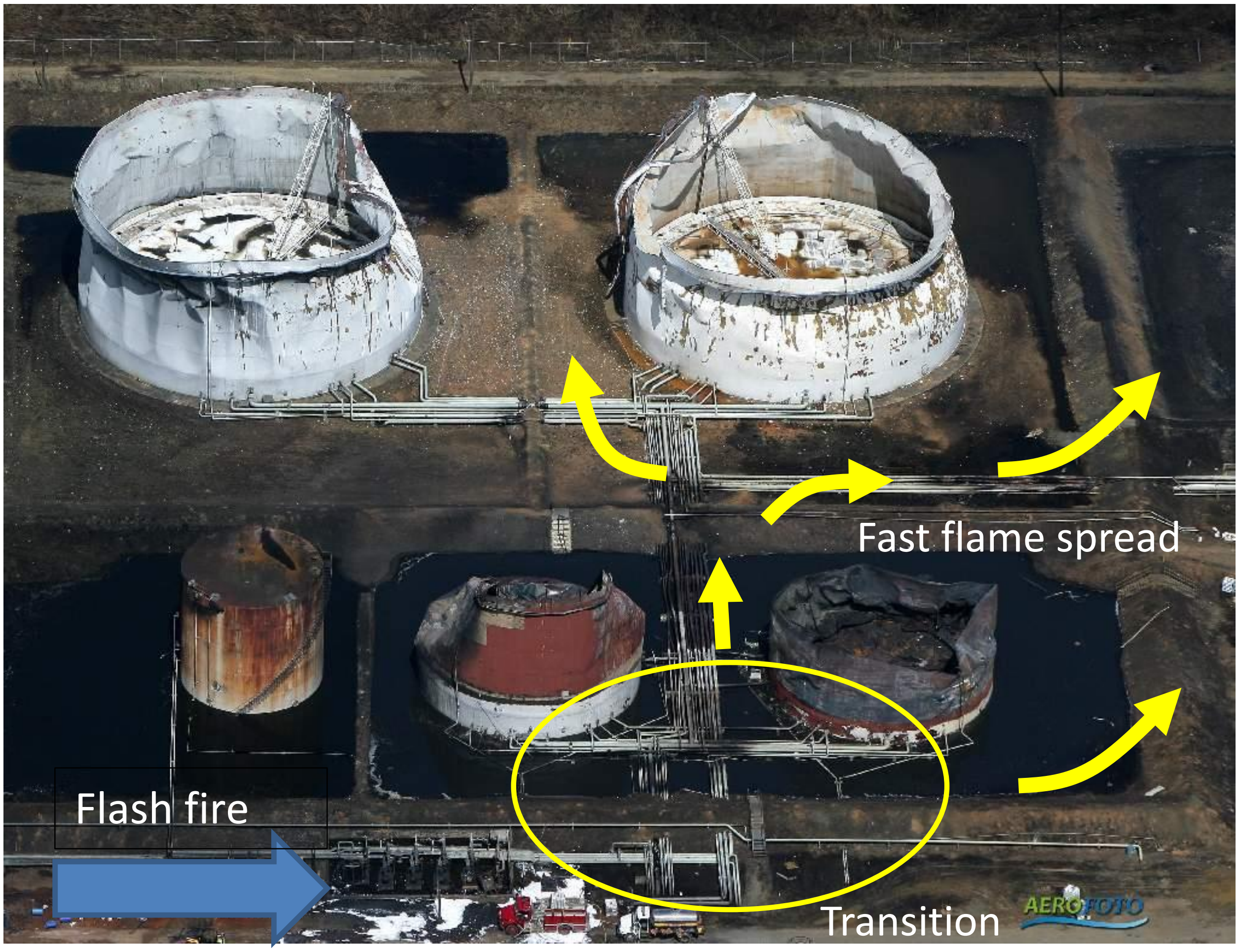


Figure 5: Area in which the San Juan explosion made a transition from flash fire to fast deflagration. After transition the flame progressed in an unsteady (episodic) manner at a sub-sonic average speed.

The review did not find any reports of very large premixed gasoline clouds (R>200 m) which burned slowly as flash fires. Notwithstanding the lack of pressure effects, such flash fires could cause deaths or injuries and would certainly leave a huge burned area. It seems likely that a high proportion of such occurrences would be reported. As discussed below, several LPG flash fires have been reported. The lack of such reports for gasoline clouds suggests that if a very large cloud develops in the context of a fuel depot, the probability of a severe explosion is high.

Our observations of the circumstances under which transition has occurred in the past provide an explanation for this: the density of pipework and other plant and the type of buildings that have provided triggers for transition are typical of fuel storage sites and could be expected in almost all sites. Again the conclusion is that if a very large cloud develops on a normal site it is appropriate to assume that the risk of transition to a severe (non-detonative) explosion is high (close to unity). With careful design and operation of sites it may be possible to reduce the risk of such transition, but currently we lack the fundamental understanding required to specify the levels of congestion and confinement that are acceptable.

The evidence at Flixborough strongly suggests that, in this case, deflagration to detonation transition (DDT) occurred in highly confined and congested areas, and that the resulting detonation propagated widely through the extensive cloud around the plant, causing massive damage. Avoiding the potential for DDT by appropriate plant layout remains a priority. In addition particular consideration should be given to the location and design of occupied buildings and safety critical equipment.

In contrast with gasoline overfill incidents, where all of the recorded incidents that caused very large clouds (R>200 m) have resulted in explosions, there are several recorded cases of large LPG clouds from pipeline failures that apparently progressed as flash fires throughout (Casella 2002). Part of the reason for this difference may be the potential for an LPG release from some source geometries to form very rich clouds in low wind speed conditions. It is difficult to distinguish between a flash fire that (initially) progresses over the top of a rich cloud and a flash fire in a pre-mixed cloud that is flammable through its full depth. Where flash fires have occurred in nil/low-wind conditions (and the depth and homogeneity can be estimated), the mass of hydrocarbons released and cloud sizes are consistent with very rich (>UFL) mixtures.

Our review of damage caused by explosions in low-lying gravity driven clouds showed a clear correlation between the depth of the cloud and the level of damage to those objects sensitive to overpressure and especially those sensitive to drag. Presumably this reflects the increased impulse associated with the explosion of deep clouds that accumulated in low-lying areas of the sites. It should be recognised that the erection of vapor barriers along the site boundary, to prevent the escape of vapor, will tend to increase the depth of the vapor cloud on the site. This may increase the destructive potential of any severe deflagration and the risk of DDT.

Explosion Mechanism

One factor that is normally ignored in theories of explosion propagation is the effect of thermal radiation. Soot production from pre–mixed flames is low and the potential for radiative heat transfer to unburned gas is generally considered to be low. However in real explosions it is common for an initial blast to disturb dust on the ground or other surfaces around the point of initiation. If the amount of dust is very high, and it is combustible the result may be a series of secondary dust explosions.

The emissivity of flames and absorption coefficient of unburned gas are greatly increased by dust contamination at much lower mass concentrations than would be required for a dust exploions: a wide range of dusts including incombustible materials have this effect. Heat transfer from flames to unburned gas is consequently much more important in explosions where there is potential for re-elevation of dust by the effects of blast ahead of the explosion front. The effect becomes very important at the large scale involved in VCEs.

The most important effects of thermal radiation occur within very large scale turbulent flames. The mixing and combustion process is driven by large scale eddies generated by unsteady separation of the boundary layers on obstacles or the ground. The flame front is stretched and contorted by these eddies – hugely increasing the area over which smaller scale eddies and eventually diffusion can drive the initiation of combustion. Although high flame speeds depend on the distortion of the flame front by obstacles, it is well known that the reactivity of the gas is also important in determining the rate of combustion in a given geometry; for example, acetylene shows a much greater tendency to flame acceleration than propane.

It can be shown (Atkinson 2015) that radiative heat transfer to pockets of unburned gas within a large flame that is lightly contaminated with dust may raise the temperature of the unburned mixture by 230°C or more. This degree of pre-warming is sufficient to raise the laminar burning velocity of propane to that of acetylene (Poinsot and Veynante 2005). It is reasonable to expect the potential for flame acceleration in such a case to be characteristic of acetylene rather than propane. The turbulence intensity required to support combustion rates consistent with a transition to a severe explosion is close to an order of magnitude lower for acetylene than propane (Atkinson 2015).

Combustion of clouds contaminated with particles is more likely to proceed in an unstable manner than is the case for uncontaminated clouds. The temperature of unburned gas will increase throughout a flame eddy which may lead to a phase of rapid burnout and potentially a localised peak in pressure. When pre-heated gas has been consumed, the rate of burning will fall until another large eddy is ignited. This means that there may be episodes of very rapid burning and localised high pressures even if the overall speed of the flame is sub-sonic. In this case the pressure waves associated with episodes of rapid burn-out would travel ahead of the flame front and could provide the means to re-elevate dust in the unburned gas. This mechanism could explain the damage observed in a number of large VCEs (San Juan, Buncefield) in which flames apparently travelled at sub-sonic speeds (on average) but showed evidence of widespread episodes of more rapid combustion.

Implications of findings for risk assessment and emergency planning at petrochemical sites

Results from this review suggest that risk assessments and emergency planning should consider both windy and nil/low-wind cases – considering different types of release together with the weather conditions in which they could produce large clouds. In simplified assessments, for sites where vapor release rates below 100 kg/s are expected, it would be appropriate to neglect windy dispersion cases and focus on nil-wind scenarios. A simplified approach of this sort is now used by HSE in the specification of planning zones around gasoline terminals (HSE SPC/TECH/GEN 43, HSE 2007).

Different approaches to mitigation may be appropriate if nil/low-wind scenarios are considered. For example: detection of gas plumes in windy conditions generally requires a large number of closely spaced devices and the chances of limiting maximum cloud size and risk of ignition by shut-down are low – because the cloud reaches its maximum size very quickly. Investment in such systems may not be warranted. On the other hand, in nil/low-wind conditions the cloud develops slowly and can be reliably detected by a small number of sensors. Shut-down on detection may then be a key element of a site's safety planning.

The problem of nil/low-wind vapor transport (the accumulation of a gas blanket with minimal detrainment) is unfamiliar to many risk assessors but it is generally better defined and (in principle) easier to solve than the more familiar dispersion in windy conditions. Approximate methods suitable for fairly level sites are available (FABIG Technical Note 12: Atkinson and Pursell, 2013). These methods require no specialist software and assessors require a minimum of training. Some examples of application of these methods in incident analysis are given in Atkinson, 2015.

In many cases high pressure (>2000 mbar) effects extended to a high proportion of the cloud and were not confined to areas where there was congested pipework or vegetation. The lack of reports of flash fires resulting from very large premixed gasoline clouds suggests that if a very large cloud develops in a normal industrial context, the probability of a severe explosion is high. This would be an appropriate assumption to make in risk assessments.

The transition to a severe explosion regime seems to require some degree of congestion or confinement. Based on the incidents studied, the following may act as triggers: confined explosions in buildings (e.g. pump houses), dense vegetation, pipe racks and other moderately congested plant. Transition to a severe but non-detonative explosion regime appears to be possible in locations with a level of congestion well below that required to give DDT.

The assumption that all severe explosions are detonations is not consistent with observed blast effects. To assume that severe explosions are possible but must be detonations is likely to significantly overestimate the potential on-site damage.

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References

Atkinson G.T. (2011a) *Blast damage to storage tanks and steel clad buildings*. Process Safety and Environmental Protection, Vol. 89, No. 6, pp. 371-381.

Atkinson G.T. (2011b) *Buncefield: A violent, episodic vapour cloud explosion* . Process Safety and Environmental Protection, Vol. 89, No. 6, pp. 371-381.

Atkinson, G. and Pursell, M. (2013) *FABIG Technical Note 12 - Vapour cloud development in over-filling incidents*, April 2013. Available from http://fabig.com/video-publications/TechnicalGuidance#,

Atkinson, G. (2015) A review of large vapour cloud incidents, HSL Report MH15/80 http://primis.phmsa.dot.gov/meetings/MtgHome.mtg?mtg=111

Briggs, G.A., Thompson, R.S. and Snyder, W.H., (1990), *Dense gas removal from a valley by crosswinds*, J. Haz. Mat., Vol **24**, p.1-38.

Buncefield Major Incident Investigation Board (2007) *The Buncefield Incident – 11th December 2005 – The Final Report of the Major Incident Investigation Board, Vol. 1*., ISBN 978-07176-6270-8. http://www.hse.gov.uk/comah/buncefield/miib-final-volume1.pdf

Casella (2002), *Report on a second study of pipeline accidents using the Health and Safety Executive'srisk assessment programs MISHAP and PIPERS,* HSE Research Report RR036.

Chen, A (2013), Structural Response to Vapour Cloud Explosions, PhD Thesis, Department of Civil and Environmental Engineering, Imperial College London, UK.

CSB (US. Chemical Safety and Hazard Investigation Board) 2015, *Caribbean Petroleum Tank Terminal Explosion and Multiple Tank Fires (October 23rd 2009) – Final Investigation Report*

DNV (2013) Phast Version 7 Software, DNV Software, London, UK. Available from http://www.dnv.com/software, accessed 19 August 2013.

Flixborough Court of Enquiry (1975), *The Flixborough Disaster,* HMSO, ISBN 011 361075 0

Grachev, A., Andreas, E., Fairall, C., Guest, P. and Persson, P. *The Critical Richardson Number and Limits of Applicability of Local Similarity Theory in the Stable Boundary Layer,* Boundary-Layer Meteorology: Volume 147, Issue 1 (2013), Page 51-82.

HSE SPC /TECH/GEN 43 Land use planning advice around large scale petrol storage sites http://www.hse.gov.uk/foi/internalops/hid_circs/technical_general/spc_tech_gen_43/

HSE 2007 http://www.hse.gov.uk/consult/condocs/cd211.htm

Havens, J. and Spicer, T.,(1988) "A dispersion model for elevated dense gas jet chemical releases", EPA Report EPA-450/4-88-006a.

MoPNG Committee (2010) (constituted by Govt. of India) *Independent Inquiry Committee Report on Indian Oil Terminal Fire at Jaipur on 29th October 2009;* completed 29th January 2010. Available from http://oisd.nic.in, accessed 19 August 2013.

Pasquill, F. (1961). The estimation of the dispersion of windborne material, The Meteorological Magazine, vol 90, No. 1063, pp 33-49.

Poinsot, T. and Veynante, D. (2005) *Theoretical and Numerical Combustion*, Pub.R.T. Edwards Inc.

SCI (2009). *Buncefield Explosion Mechanism Phase 1,* Research Report RR718 HSE Books, Sudbury (http://www.hse.gov.uk/research/rrhtm/rr718.htm).

SCI (2014) *Dispersion and Explosion Characteristics of Large Vapour Clouds Volume 1 – Summary Report,* Steel Construction Institute, SCI Document ED023

Van den Berg, A.C 1985 The multi-energy method: A framework for vapour cloud explosion blast prediction, Journal of Hazardous Materials, Volume 12, Issue 1, , Pages 1-10